Practical Software Diversification for WebAssembly

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Abstract

Keywords: Lorem, Ipsum, Dolor, Sit, Amet

Sammanfattning

LIST OF PAPERS

1. **WebAssembly Diversification for Malware Evasion**
   Javier Cabrera-Arteaga,Tim Toady, Martin Monperrus, Benoit Baudry
   Computers & Security, Volume 131, 2023, 17 pages
   `https://www.sciencedirect.com/science/article/pii/S01674048230 02067`

2. **Wasm-mutate: Fast and Effective Binary Diversification for WebAssembly**
   Javier Cabrera-Arteaga, Nicholas Fitzgerald, Martin Monperrus, Benoit Baudry
   Under review, 17 pages
   `https://arxiv.org/pdf/2309.07638.pdf`

3. **Multi-Variant Execution at the Edge**
   Javier Cabrera-Arteaga,Pierre Laperdrix, Martin Monperrus, Benoit Baudry
   Moving Target Defense (MTD 2022), 12 pages
   `https://dl.acm.org/doi/abs/10.1145/3560828.3564007`

4. **CROW: Code Diversification for WebAssembly**
   Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus
   Measurements, Attacks, and Defenses for the Web (MADWeb 2021), 12 pages
   `https://doi.org/10.14722/madweb.2021.23004`

5. **Superoptimization of WebAssembly Bytecode**
   Javier Cabrera-Arteaga,Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus
   Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs, 4 pages
   `https://doi.org/10.1145/3397537.3397567`

6. **Scalable Comparison of JavaScript V8 Bytecode Traces**
   Javier Cabrera-Arteaga,Martin Monperrus, Benoit Baudry
   11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages (SPLASH 2019), 10 pages
   `https://doi.org/10.1145/3358504.3361228`

ACKNOWLEDGEMENT

Contents

Part I

Thesis

1
INTRODUCTION

TODO Recent papers first. Mention Workshops instead in conference. "Procedings of XXXX". Add the pages in the papers list.

1.1 Background

TODO Motivate with the open challenges.

1.2 Problem statement

TODO Problem statement **TODO** Set the requirements as R1, R2, then map each contribution to them.

1.3 Automatic Software diversification requirements

1. **1:** **TODO** Requirement 1

1.4 List of contributions

C1: Methodology contribution: We propose a methodology for generating software diversification for WebAssembly and the assessment of the generated diversity.

C2: Theoretical contribution: We propose theoretical foundation in order to improve Software Diversification for WebAssembly.

C3: Automatic diversity generation for WebAssembly: We generate WebAssembly program variants.

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Contribution	Research papers				
	P1	P2	P3	P4	P5
C1	x	x		x	x
C2	x	x			
C3	x	x	x		
C4	x	x	x		
C5			x		
C6	x	x	x	x	x

Table 1.1: *Mapping of the contributions to the research papers appended to this thesis.*

C4: Software Diversity for Defensive Purposes: We assess how generated WebAssembly program variants could be used for defensive purposes.

C5: Software Diversity for Offensives Purposes: We assess how generated WebAssembly program variants could be used for offensive purposes, yet improving security systems.

C6: Software Artifacts: We provide software artifacts for the research community to reproduce our results.

   TODO Make multi column table

1.5   Summary of research papers

P1: Superoptimization of WebAssembly Bytecode.

P2: CROW: Code randomization for WebAssembly bytecode.

P3: Multivariant execution at the Edge.

P4: Wasm-mutate: Fast and efficient software diversification for WebAssembly.

P5: WebAssembly Diversification for Malware evasion.

1.6   Thesis outline

2
BACKGROUND AND STATE OF THE ART

THIS chapter discusses the state-of-the-art in the areas of WebAssembly and Software Diversification. In Section 2.1 ... In Section 2.2 ... **TODO** Describe chapter

2.1 WebAssembly

The W3C publicly announced the WebAssembly (Wasm) language in 2017 as the four scripting language supported in all major web browser vendors. Wasm is a binary instruction format for a stack-based virtual machine and was officially consolidated by the work of Haas et al. [**?**] in 2017 and extended by Rossberg in 2018 [**?**]. It is designed to be fast, portable, self-contained and secure, and it promises to outperform JavaScript execution. Since 2017, the adoption of Wasm keeps growing. For example; Adobe, announced a full online version of Photoshop[1] written in WebAssembly; game companies moved their development from JavaScript to Wasm like is the case of a full Minecraft version[2].

Moreover, WebAssembly has been evolving outside web browsers since its first announcement. Some works demonstrated that using WebAssembly as an intermediate layer is better in terms of startup and memory usage than containerization and virtualization [**?** **?**]. Consequently, in 2019, the

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[1] https://twitter.com/Adobe/status/1453034805004685313?s=20&t=Zf1N7-WmzecAOK4V8R6
9lw

[2] https://satoshinm.github.io/NetCraft/

Bytecodealliance proposed WebAssembly System Interface (WASI) [**?**]. WASI pioneered the execution of Wasm with a POSIX system interface protocol, making it possible to execute Wasm closer to the underlying operating system. Therefore, it standardizes the adoption of Wasm in heterogeneous platforms [**?**], making it suitable for standalone and backend execution scenarios [**? ?**].

2.1.1 From source code to WebAssembly

WebAssembly programs are compiled from source languages like C/C++, Rust, or Go, which means that it can benefit from the optimizations of the source language compiler. The resulting Wasm program is like a traditional shared library, containing instruction codes, symbols, and exported functions. A host environment is in charge of complementing the Wasm program, such as providing external functions required for execution within the host engine. For instance, functions for interacting with an HTML page's DOM are imported into the Wasm binary when invoked from JavaScript code in the browser.

In Listing 2.1 and Listing 2.2, we illustrate a C program and its corresponding Wasm binary. The C function includes heap allocation, external function usage, and a function definition featuring a loop, conditional branching, function calls, and memory accesses. The Wasm code in Listing 2.2 displays the textual format of the generated Wasm (Wat)[3].

```c
// Some raw data
const int A[250];

// Imported function
int ftoi(float a);

int main() {
    for(int i = 0; i < 250; i++) {
        if (A[i] > 100)
            return A[i] + ftoi(12.54);
    }

    return A[0];
}
```

Listing 2.1: *Example C program which includes heap allocation, external function usage, and a function definition featuring a loop, conditional branching, function calls, and memory accesses.*

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[3]The WAT text format is mostly for human readability and for low-level manual modification.

```
 1 ; WebAssembly magic bytes(\0asm) and version (1.0) ;
 2 (module
 3 ; Type section: 0x01 0x00 0x00 0x00 0x13 ... ;
 4   (type (;0;) (func (param f32) (result i32)))
 5   (type (;1;) (func))
 6   (type (;2;) (func (result i32)))
 7 ; Import section: 0x02  0x00 0x00 0x00 0x57 ... ;
 8   (import "env" "ftoi" (func $ftoi (type 0)))
 9 ; Custom section: 0x00 0x00 0x00 0x00 0x7E ;
10   (@custom "name" "...")
11 ; Code section: 0x03 0x00 0x00 0x00 0x5B... ;
12   (func $main (type 2) (result i32)
13     (local i32 i32)
14     i32.const -1000
15     local.set 0
16     block   ;label = @1;
17       loop   ;label = @2;
18         i32.const 0
19         local.get 0
20         i32.add
21         i32.load
22         local.tee 1
23         i32.const 101
24         i32.ge_s
25         br_if 1 ;@1;
26         local.get 0
27         i32.const 4
28         i32.add
29         local.tee 0
30         br_if 0 ;@2;
31       end
32       i32.const 0
33       return
34     end
35     f32.const 0x1.9147aep+3
36     call $ftoi
37     local.get 1
38     i32.add)
39 ; Memory section: 0x05 0x00 0x00 0x00 0x03 ... ;
40   (memory (;0;) 1)
41 ; Global section: 0x06 0x00 0x00 0x00 0x11.. ;
42   (global (;4;) i32 (i32.const 1000))
43 ; Export section: 0x07 0x00 0x00 0x00 0x72 ... ;
44   (export "memory" (memory 0))
45   (export "A" (global 2))
46 ; Data section: 0x0d 0x00 0x00 0x03 0xEF  ... ;
47   (data $data (0) "\00\00\00\00...")
48 ; Custom section: 0x00 0x00 0x00 0x00 0x2F ;
49   (@custom "producers" "...")
50 )
```

Listing 2.2: *Wasm code for Listing 2.1. The example Wasm code illustrates the translation from C to Wasm in which several high-level language features are translated into multiple Wasm instructions.*

2.1.2 WebAssembly's binary format

The Wasm binary format is close to machine code and already optimized, being a consecutive collection of sections. In Figure 2.1 we show the binary format of a Wasm section. A Wasm section starts with a 1-byte section ID, followed

by a 4-byte section size, and concludes with the section content, which precisely matches the size indicated earlier. A Wasm binary contains sections of 13 types, each with a specific semantic role and placement within the module. Each section is optional, where an omitted section is considered empty. In the following text, we summarize each one of the 13 types of Wasm sections, providing their name, ID, and purpose. In addition, some sections are annotated as comments in the Wasm code in Listing 2.2.
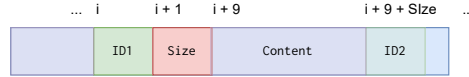
Figure 2.1: *Memory byte representation of a WebAssembly binary section, starting with a 1-byte section ID, followed by an 8-byte section size, and finally the section content.*

Custom Section (00) : Comprises two parts: the section name and arbitrary content. Primarily used for storing metadata, such as the compiler used to generate the binary (see lines 9 and 48 of Listing 2.2). This type of section has no order constraints with other sections and is optional. Compilers usually skip this section when consuming a WebAssembly binary.

Type Section (01) : Contains the function signatures for functions declared or defined within the binary (see lines 3 to 6 in Listing 2.2). Functions may share the same function signature. This section must occur only once in a binary. It can be empty.

Import Section (02) : Lists elements imported from the host, including functions, memories, globals, and tables (see line 8 in Listing 2.2). This section is needed to enable code and data sharing with the host engine and other modules. It must occur only once in a binary. It can be empty.

Function Section (03) : Details functions defined within the binary. It essentially maps Type section entries to Code section entries. The text format already maps the function index to its name, as shown in lines 12 to 38 of Listing 2.2. This section must occur only once in a binary and, it can be empty.

Table Section (04) : Groups functions with identical signatures to control indirect calls. It must occur only once in a binary. It can be empty. The example code in Listing 2.2 does not include a Table Section.

Memory Section (05) : Specifies the number and initial size of unmanaged linear memories (see line 40 in Listing 2.2). It must occur only once in a binary. It can be empty.

Global Section (06) : Defines global variables as managed memory for use and

sharing between functions in the WebAssembly binary (see line 42 of Listing 2.2). It must occur only once in a binary. It can be empty.

Export Section (07) : Declares elements like functions, globals, memories, and tables for host engine access (see lines 44 and 45 of Listing 2.2). It must occur only once in a binary. It can be empty.

Start Section (08) : Designates a function to be called upon binary readiness, initializing the WebAssembly program state before executing any exported functions. It must occur only once in a binary. It can be empty. The example code in Listing 2.2 does not include a Start Section, i.e. there is no function to call when the binary is initialized.

Element Section (09) : Contains elements to initialize the binary tables. It must occur only once in a binary. It can be empty. The example code in Listing 2.2 does not include an Element Section.

Code Section (10) : Contains the body of functions defined in the Function section. Each entry consists of local variables used and a list of instructions (see lines 12 to 38 in Listing 2.2). It must occur only once in a binary. It can be empty.

Data Section (11) : Holds data for initializing unmanaged linear memory. Each entry specifies the offset and data to be placed in memory (see line 47 in Listing 2.2). It must occur only once in a binary. It can be empty.

Data Count Section (12) : Primarily used for validating the Data Section. If the segment count in the Data Section mismatches the Data Count, the binary is considered malformed. The example code in Listing 2.2 does not include a Data Count Section. It must occur only once in a binary. It can be empty.

Due to its organization into a contiguous array of sections, a Wasm binary can be processed efficiently. For example, this structure allows compilers to speed up the compilation process through parallel parsing or just by ignoring *Custom Sections*. Additionally, the use of the LEB128[4] encoding of instructions of the *Code Section* further compacts the binary. As a result, Wasm binaries are not only fast to process but also quick to transmit over a network.

2.1.3 WebAssembly's runtime structure

The WebAssembly runtime structure is described in the WebAssembly specification by enunciating 10 key components: the Store, Module Instances, Table Instances, Export Instances, Import Instances, the Execution Stack, Memory Instances, Global Instances, Function Instances and Locals. These

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[4]https://en.wikipedia.org/wiki/LEB128

components are particularly significant in maintaining the state of a WebAssembly program during its execution. In the following text, we provide a brief description of each runtime component. Notice that, the runtime structure is an abstraction that serves to validate the execution of a Wasm binary.

Store : The WebAssembly store represents the global state and is a collection of instances of functions, tables, memories, and globals. Each of these instances is uniquely identified by an address, which is usually represented as an i32 integer.

Module Instances : A module instance is a runtime representation of a loaded and initialized WebAssembly module. It contains the runtime representation of all the definitions within a module, including functions, tables, memories, and globals, as well as the module's exports and imports.

Table instances : A table instance is a vector of *function instances* with the same signature. They are used to validate and support indirect function calls during runtime. A table instance can be modified through table instructions from the function bodies.

Export Instances : Export instances represent the functions, tables, elements, globals or memories that are exported by a Wasm binary to the host environment.

Import Instances : Import instances represent the functions, tables, elements, globals or memories that are imported into a module from the host environment.

The Execution Stack holds typed values, labels and control frames, with labels handling block instructions, loops, and function calls. Values inside the stack can be of the only static types allowed in Wasm 1.0, `i32` for 32 bits signed integer, `i64` for 64 bits signed integer, `f32` for 32 bits float and `f64` for 64 bits float. Therefore, abstract types, such as classes, objects, and arrays, are not natively supported. Instead, during compilation, such types are transformed into primitive types and stored in the linear memory.

Memory Instances represent the unmanaged linear memory of a WebAssembly program, consisting of a contiguous array of bytes. Memory instances are accessed with `i32` pointers (integer of 32 bits). Memory instances are usually bound in browser engines to 4Gb of size, and it is only shareable between the process that instantiates the WebAssembly module and the binary itself.

Global Instances : A global instance is a global variable with a value and a mutability flag, indicating whether the global can be modified or is immutable. Global variables are part of the managed data, i.e., their allocation and memory placement are managed by the host engine. Global variables are only accessible by their declaration index, and it is not possible to dynamically address them.

Locals : Locals are mutable variables that are local to a specific function instance,

i.e. locals are only accessible through their index related to the executing function instance. As globals, locals are part of the managed data.

Function Instances : are closures over the runtime module instance. A function instance groups locals and a function body. Locals are typed variables that are local to a specific function invocation as previously discussed. The function body is a sequence of instructions that are executed when the function is called. Each instruction either reads from the stack, writes to the stack, or modifies the control flow of the function. Recalling the example Wasm binary previously showed, the local variable declarations and typed instructions that are evaluated using the stack can be appreciated between Line 7 and Line 32 in Listing 2.2. Each instruction reads its operands from the stack and pushes back the result. In the case of Listing 2.2, the result value of the main function is the calculation of the last instruction, `i32.add`. As the listing also shows, instructions are annotated with a numeric type.

Definition 1. *Along with this dissertation, as the work of Lehmann et al. [?], we refer to managed and unmanaged data to differentiate between the data that is managed by the host engine and the data that is managed by the WebAssembly program respectively.*

2.1.4 WebAssembly's control flow

In WebAssembly, a defined function instructions are organized into blocks, with the function's starting point serving as the root block. Unlike traditional assembly code, control flow structures in Wasm jump between block boundaries rather than arbitrary positions within the code. Each block might specify the required stack state before execution and the resulting stack state after its instructions have run. This stack state is used to validate the binary during compilation and to ensure that the stack is in a valid state before executing the block's instructions. Blocks in Wasm are explicit, indicating, where they start and end. By design, each block cannot reference or execute code from outer blocks.

Control flow within a function is managed through three types of break instructions: unconditional break, conditional break, and table break. Importantly, each break instruction is limited to jumping to one of its enclosing blocks. Unlike standard blocks, where breaks jump to the end of the block, breaks within a loop block jump to the block's beginning, effectively restarting the loop. To illustrate this, Listing 2.3 provides an example comparing a standard block and a loop block in a Wasm function.

```
block                             loop
    block                             ...
        br 1    ; Jump instructions   br 0   ;first-order break;
                are annotated with the ...
                depth of the block they
                jump to;              end   ; end instructions break
                                            the block and jump to next
    end                                     instruction;
end                               ...
...
```

Listing 2.3: *Example of breaking a block and a loop in WebAssembly.*

Each break instruction includes the depth of the enclosing block as an operand. This depth is used to identify the target block for the break instruction. For example, in the left-most part of the previously discussed listing, a break instruction with a depth of 1 would jump past two enclosing blocks.

2.1.5 WebAssembly's ecosystem

WebAssembly programs are tailored for execution in host environments, most notably web browsers. The WebAssembly ecosystem is a diverse landscape, featuring a multitude of stakeholders and a comprehensive suite of tools to meet various requirements [?]. In this section, we delineate two key categories of tools within this ecosystem: compilers and executors. Compilers are responsible for converting source code into WebAssembly binaries, while executors handle a range of tasks including validation, optimization, machine code transpilation, and actual execution of these WebAssembly binaries. Executors are often found in browser clients, among other platform

Compilers transform source code into WebAssembly binaries. For example, LLVM has offered WebAssembly as a backend option since its 7.1.0 release[5], supporting a diverse set of frontend languages like C/C++, Rust, Go, and AssemblyScript[6]. In parallel developments, the KMM framework[7] has incorporated WebAssembly as a compilation target, and the Javy approach[8] focuses on encapsulating JavaScript code within isolated WebAssembly binaries. This latter is achieved by porting both the engine and the source code into a secure WebAssembly environment. Similarly, Blazor also enables the compilation of C code into WebAssembly binaries for browser execution[9].

From a security standpoint, WebAssembly programs are designed without a standard library and are prohibited from direct interactions with the operating system. Instead, the host environment offers a predefined set of functions that

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[5]https://github.com/llvm/llvm-project/releases/tag/llvmorg-7.1.0
[6]A subset of the TypeScript language
[7]https://kotlinlang.org/docs/wasm-overview.html
[8]https://github.com/bytecodealliance/javy
[9]https://dotnet.microsoft.com/apps/aspnet/web-apps/blazor

can be imported into the WebAssembly program. It falls upon the compilers to specify which functions from the host environment will be imported by the WebAssembly application.

Browser engines like V8[10] and SpiderMonkey[11] are at the forefront of executing WebAssembly binaries in browser clients. These engines leverage Just-In-Time (JIT) compilers to convert WebAssembly into machine code. This translation is typically a straightforward one-to-one mapping, given that WebAssembly is already an optimized format closely aligned with machine code, as previously discussed in Subsection 2.1.2. For example, V8 just employs quick, rudimentary optimizations, such as constant folding and dead code removal, to guarantee fast readiness for a Wasm binary to execute.[12]

Standalone engines: Wasm has expanded beyond browser environments, largely due to the WASI[**?**]. It standardizes the interactions between host environments and WebAssembly modules through a POSIX-like interface. Wasm compilers can generate binaries that use WASI. Standalone engines can then execute these binaries in a variety of environments, including cloud, server, and IoT devices. For example, standalone engines like WASM3[13], Wasmer[14], Wasmtime[15], WAVM[16], and Sledge[**?**] have emerged to support WebAssembly and WASI. In a similar vein, Singh et al.[**?**] introduced a virtual machine for WebAssembly tailored for Arduino-based devices. Salim et al.[**?**] proposed TruffleWasm, an implementation of WebAssembly hosted on Truffle and GraalVM. Additionally, SWAM[17] stands out as WebAssembly interpreter implemented in Scala. Finally, WaVe[**?**] offers a WebAssembly interpreter featuring mechanized verification of the WebAssembly-WASI interaction with the underlying operating system.

2.1.6 WebAssembly's binary analysis

As the WebAssembly ecosystem continues to grow, the need for robust tools to ensure its security and reliability has increased. To address this, a variety of tools have been developed that employ different strategies to identify vulnerabilities in WebAssembly programs. In the following text we provide a brief overview of the most relevant tools in this space w.r.t static and dynamic analysis, as well as specialized malware detection.

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[10]https://chromium.googlesource.com/v8/v8.git
[11]https://spidermonkey.dev/
[12]This analysis was corroborated through discussions with the V8 development team and through empirical studies in one of our contributions[**?**]
[13]https://github.com/wasm3/wasm3
[14]https://wasmer.io/
[15]https://github.com/bytecodealliance/wasmtime
[16]https://github.com/WAVM/WAVM
[17]https://github.com/satabin/swam

Static and dynamic analysis: Tools like Wassail[**?**], SecWasm[**?**], Wasmati[**?**], and Wasp[**?**] leverage techniques such as information flow control, code property graphs, control flow analysis, and concolic execution to detect vulnerabilities in Wasm binaries. Remarkably, VeriWasm[**?**] stands out as a static offline verifier specifically designed for native x86-64 binaries compiled from WebAssembly. In the dynamic analysis counterpart, tools like TaintAssembly[**?**], Wasabi[**?**], and Fuzzm[**?**] offer similar functionalities in vulnerability detection. Stiévenart and colleagues have introduced a dynamic approach to slice WebAssembly programs based on Observational-Based Slicing (ORBS)[**?** **?**]. Hybrid methods have also gained traction, with tools like CT-Wasm[**?**] enabling the verifiably secure implementation of cryptographic algorithms in WebAssembly.

Specialized Malware Detection: Cryptomalwares have a wide presence in the web since the first days of Wasm. The main reason is that mining algorithms using CPUs moved to Wasm for obvious performance reasons [**?**]. In cryptomalware detection, tools like MineSweeper[**?**], MinerRay[**?**], and MINOS[**?**] utilize static analysis through machine learning techniques to detect browser cryptomalwares. Conversely, tools like SEISMIC[**?**], RAPID[**?**], and OUTGuard[**?**] seek the same goal with dynamic analysis techniques. Remarkably, VirusTotal[18], packaging more than 60 commercial antivirus as back-boxes, detects cryptomalware in Wasm binaries.

2.1.7 WebAssembly's security

While WebAssembly is engineered to be deterministic, well-typed, and to adhere to a structured control flow, the ecosystem is still emerging and faces various security vulnerabilities. These vulnerabilities pose risks to both the consumers and the WebAssembly binaries themselves. Side-channel attacks, in particular, are a significant concern. For example, Genkin et al. have shown that WebAssembly can be exploited to exfiltrate data through cache timing-side channels [**?**]. Similarly, research by Maisuradze and Rossow demonstrates the feasibility of speculative execution attacks on WebAssembly binaries [**?**]. Rokicki et al. further reveal the potential for port contention side-channel attacks on WebAssembly binaries in browsers [**?**]. Additionally, studies by Lehmann et al. and Stiévenart and colleagues indicate that vulnerabilities in C/C++ source code can propagate into WebAssembly binaries [**?** **?**]. This dissertation introduces a comprehensive set of tools aimed at preemptively enhancing WebAssembly security through Software Diversification and at improving testing rigor within the ecosystem.

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[18]https://www.virustotal.com

2.2 Software diversification

2.2.1 Generating Software Diversification

2.2.2 Variants generation

2.2.3 Variants equivalence

TODO Automatic, SMT based **TODO** Take a look to Jackson thesis, we have a similar problem he faced with the superoptimization of NaCL **TODO** By design **TODO** Introduce the notion of rewriting rule by Sasnaukas. `https://link.springer.com/chapter/10.1007/978-3-319-68063-7_13`

2.2.4 Defensive Diversification

2.2.5 Offensive Diversification

3

AUTOMATIC SOFTWARE DIVERSIFICATION FOR WEBASSEMBLY

THE process of generating WebAssembly binaries starts with the original source code, which is then processed by a compiler to produce a WebAssembly binary. This compiler is generally divided into three main components: a frontend that converts the source code into an intermediate representation, an optimizer that transforms this representation usually for performance, and a backend that compiles the final WebAssembly binary. For example, LLVM uses this architecture [?], supporting several programming languages like C, C++, and Rust for several backed architectures, including WebAssembly.

On the other hand, Software Diversification, a preemptive security measure, can be integrated at various stages of this compilation process. However, applying diversification at the front-end has its limitations, as it would need a unique diversification mechanism for each language compatible with the frontend component. Conversely, diversification at later compiler stages, such as the optimizer or backend, offers a more practical alternative.

Significantly, a study by Hilbig et al. reveals that 70% of WebAssembly binaries are generated using LLVM-based compilers. This makes the latter stages of the LLVM compiler an ideal point for introducing practical Wasm diversification techniques. Thus, our compiler-based strategies, represented in red and green in Figure 3.1, introduce a diversifier component into the LLVM pipeline. This component generates LLVM IR variants, thereby creating artificial software diversity for WebAssembly. Specifically, we propose two tools: CROW, which generates WebAssembly program variants, and MEWE, which packages these variants to enable multivariant execution [?]. Alternatively, diversification can

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be directly applied to the WebAssembly binary, offering a language and compiler-agnostic approach. Our binary-based strategy, WASM-MUTATE, represented in blue in Figure 3.1, employs rewriting rules on an e-graph data structure to generate a variety of WebAssembly program variants.
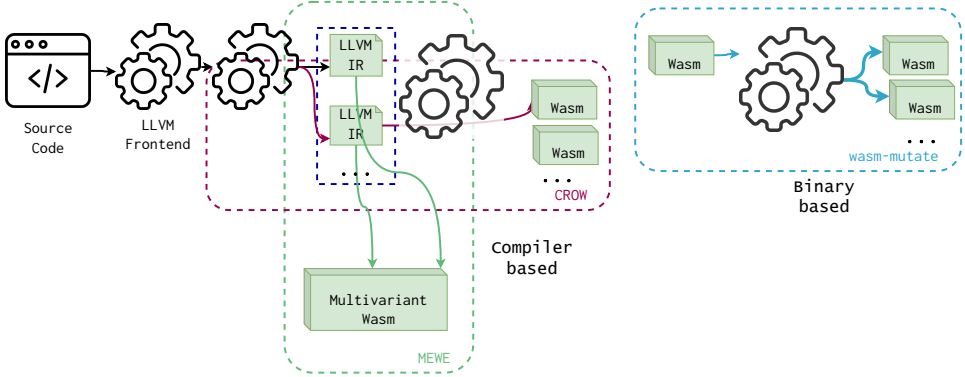

Figure 3.1: *Approach landscape containing our three technical contributions: CROW squared in red, MEWE squared in green and WASM-MUTATE squared in blue. We annotate where our contributions, compiler-based and binary-based, stand in the landscape of generating WebAssembly programs.*

This dissertation contributes to the field of Software Diversification for WebAssembly by presenting two primary strategies: compiler-based and binary-based. Within this chapter, we introduce three technical contributions: CROW, MEWE, and WASM-MUTATE. We also compare these contributions, highlighting their complementary nature. Additionally, we provide the artifacts for our contributions to promote open research and reproducibility of our main takeaways.

3.1   CROW: Code Randomization of WebAssembly

This section details CROW [**?**], represented as the red squared tooling in Figure 3.1. CROW is designed to produce functionally equivalent Wasm variants from the output of an LLVM front-end, utilizing a custom Wasm LLVM backend.

Figure 3.2 illustrates CROW's workflow in generating program variants, a process compound of two core stages: *exploration* and *combining*. During the *exploration* stage, CROW processes every instruction within each function of the LLVM input, creating a set of functionally equivalent code variants. This process ensures a rich pool of options for the subsequent stage. In the *combining* stage, these alternatives are assembled to form diverse LLVM IR variants, a

task achieved through the exhaustive traversal of the power set of all potential combinations of code replacements. The final step involves the custom Wasm LLVM backend, which compiles the crafted LLVM IR variants into Wasm binaries.
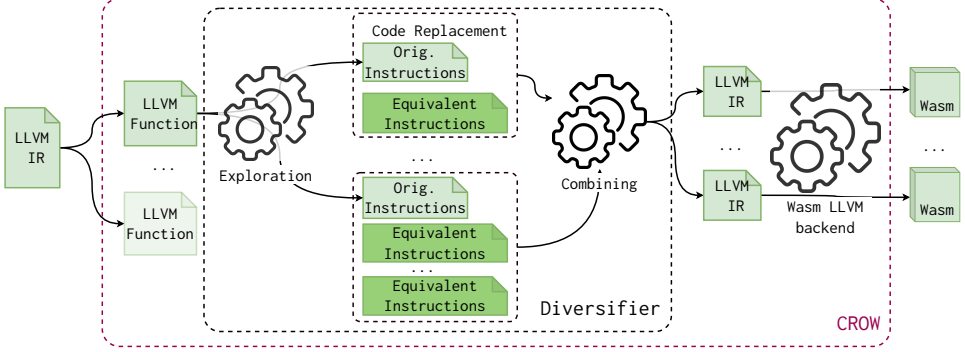

Figure 3.2: *CROW components following the diagram in Figure 3.1. CROW takes LLVM IR to generate functionally equivalent code replacements. Then, CROW assembles program variants by combining them. Figure taken from [**?**].*

3.1.1 Enumerative synthesis

The cornerstone of CROW's exploration mechanism is its code replacement generation strategy, which is inspired by the superdiversifier methodology proposed by Jacob et al. [**?**]. The search space for generating variants is delineated through an enumerative synthesis process, which systematically produces all possible code replacements for each instruction and its data flow graph in the original program. If a code replacement is identified to perform identically to the original program, it is reported as a functionally equivalent variant. This equivalence is confirmed using a theorem solver for rigorous verification.

Concretely, CROW is developed by modifying the enumerative synthesis implementation found in Souper [**?**   ], an LLVM-based superoptimizer. Specifically, CROW constructs a Data Flow Graph for each LLVM instruction that returns an integer. Subsequently, it generates all viable expressions derived from a selected subset of the LLVM Intermediate Representation language for each DFG. The enumerative synthesis process incrementally generates code replacements, starting with the simplest expressions (those composed of a single instruction) and gradually increasing in complexity. The exploration process continues either until a timeout occurs or the size of the generated replacements exceeds a predefined threshold.

Notice that the search space increases exponentially with the size of the language used for enumerative synthesis. To mitigate this issue, we prevent CROW from synthesizing instructions without correspondence in the Wasm backend, effectively reducing the searching space. For example, creating an expression having the `freeze` LLVM instructions will increase the searching space for instruction without a Wasm's opcode in the end. Moreover, we disable the majority of the pruning strategies of Souper for the sake of more program variants. For example, Souper prevents the generation of commutative operations during the searching. On the contrary, CROW still uses such transformation as a strategy to generate program variants.

Leveraging the ascending nature of its enumerative synthesis process, CROW is capable of creating variants that may outperform the original program in both size and efficiency. For instance, the first functionally equivalent transformation identified is typically the most optimal in terms of code size. This approach offers developers a range of performance options, allowing them to balance between diversification and performance without compromising the latter. CROW applies these code transformations incrementally. For instance, if a suitable replacement is identified that can be applied at N different locations in the original program, CROW will generate N distinct program variants, each with the transformation applied at a unique location. This approach leads to a combinatorial explosion in the number of available program variants, especially as the number of possible replacements increases.

The last stage at CROW involves a custom Wasm LLVM backend, which generates the Wasm programs. For it, we remove all built-in optimizations in the LLVM backend that could reverse Wasm variants, i.e., we disable all optimizations in the Wasm backend that could reverse the CROW transformations.

3.1.2 Constant inferring

CROW, inherently adds a new transformation strategy that leads to more Wasm program variants, *constant inferring*. In concrete, Souper infers pieces of code as a single constant assignment and this is ported to CROW. This strategy mostly focuses on variables that are used to control branches. After a *constant inferring*, the generated program is considerably different from the original program, being suitable for diversification.

Let us illustrate the case with an example. The Babbage problem code in Listing 3.1 is composed of a loop that stops when it discovers the smallest number that fits with the Babbage condition in Line 4.

```
1    int babbage() {                           1    int babbage() {
2        int current = 0,                      2        int current = 25264;
3            square;                            3
4        while ((square=current*current) %     4
            ↪ 1000000 != 269696) {             5
5            current++;                         6
6        }                                      7
7        printf ("The number is %d\n",         8
            ↪ current);                        9        printf ("The number is %d\n", current);
8        return 0 ;                            10        return 0 ;
9    }                                         11    }
```

Listing 3.1: *Babbage problem. Taken from [?].*

Listing 3.2: *Constant inferring transformation over the original Babbage problem in Listing 3.1. Taken from [?].*

In theory, this value can also be inferred by unrolling the loop the correct number of times with the LLVM toolchain. However, standard LLVM tools cannot unroll the **while**-loop because the loop count is too large. CROW deals with this case, generating the program in Listing 3.2. It infers the value of `current` in Line 2 such that the Babbage condition is reached. Therefore, the condition in the loop will always be false. Then, the loop is dead code and is removed in the final compilation. The new program in Listing 3.2 is remarkably smaller and faster than the original code. Therefore, it offers differences both statically and at runtime[1]

3.1.3 CROW instantiation

Let us illustrate how CROW works with the example code in Listing 3.3. The `f` function calculates the value of $2 * x + x$ where `x` is the input for the function. CROW compiles this source code and generates the intermediate LLVM bitcode in the left most part of Listing 3.4. CROW potentially finds two integer returning instructions to look for variants, as the right-most part of Listing 3.4 shows.

```
1    int f(int x) {
2        return 2 * x + x;
3    }
```

Listing 3.3: *C function that calculates the quantity $2x + x$.*

---

[1]Notice that for the sake of illustration, we show both codes in C language, this process inside CROW is performed directly in LLVM IR.

```
define i32 @f(i32) {            Replacement candidates    Replacement candidates for
                                    for code_1                    code_2
  %2 = mul nsw i32 %0,2
  %3 = add nsw i32 %0,%2    %2 = mul nsw i32 %0,2      %3 = add nsw i32 %0,%2

  ret i32 %3               %2 = add nsw i32 %0,%0      %3 = mul nsw %0, 3:i32
}
                           %2 = shl nsw i32 %0, 1:i32
define i32 @main() {
  %1 = tail call i32 @f(
      i32 10)
  ret i32 %1
}
```

Listing 3.4: *LLVM's intermediate representation program, its extracted instructions and replacement candidates. Gray highlighted lines represent original code, green for code replacements.*

```
%2 = mul nsw i32 %0,2              %2 = mul nsw i32 %0,2
%3 = add nsw i32 %0,%2            %3 = mul nsw %0, 3:i32

%2 = add nsw i32 %0,%0            %2 = add nsw i32 %0,%0
%3 = add nsw i32 %0,%2            %3 = mul nsw %0, 3:i32

%2 = shl nsw i32 %0, 1:i32        %2 = shl nsw i32 %0, 1:i32
%3 = add nsw i32 %0,%2            %3 = mul nsw %0, 3:i32
```

Listing 3.5: *Candidate code replacements combination. Orange highlighted code illustrate replacement candidate overlapping.*

CROW, detects `code_1` and `code_2` as the enclosing boxes in the left most part of Listing 3.4 shows. CROW synthesizes $2 + 1$ candidate code replacements for each code respectively as the green highlighted lines show in the right most parts of Listing 3.4. The baseline strategy of CROW is to generate variants out of all possible combinations of the candidate code replacements, *i.e.,* uses the power set of all candidate code replacements.

In the example, the power set is the cartesian product of the found candidate code replacements for each code block, including the original ones, as Listing 3.5 shows. The power set size results in 6 potential function variants. Yet, the generation stage would eventually generate 4 variants from the original program. CROW generated 4 statically different Wasm files, as Listing 3.6 illustrates. This gap between the potential and the actual number of variants is a consequence of the redundancy among the bitcode variants when composed into one. In other words, if the replaced code removes other code blocks, all possible combinations having it will be in the end the same program. In the example case, replacing `code_2` by `mul nsw %0, 3`, turns `code_1` into dead code, thus, later replacements generate the same program variants. The rightmost part of Listing 3.5 illustrates how for three different combinations, CROW produces the same variant. We call this phenomenon a *code replacement overlapping.*

```
func $f (param i32) (result i32)          func $f (param i32) (result i32)
  local.get 0                               local.get 0
  i32.const 2                               i32.const 1
  i32.mul                                   i32.shl
  local.get 0                               local.get 0
  i32.add                                   i32.add


func $f (param i32) (result i32)          func $f (param i32) (result i32)
  local.get 0                               local.get 0
  local.get 0                               i32.const 3
  i32.add                                   i32.mul
  local.get 0
  i32.add
```

Listing 3.6: *Wasm program variants generated from program Listing 3.3.*

One might think that a reasonable heuristic could be implemented to avoid such overlapping cases. Instead, we have found it easier and faster to generate the variants with the combination of the replacement and check their uniqueness after the program variant is compiled. This prevents us from having an expensive checking for overlapping inside the CROW code.

> **Contribution paper and artifact**
>
> CROW, as a compiler-based approach, leverages enumerative synthesis to generate functionally equivalent code replacements and assembles them into diverse Wasm program variants.
> CROW is fully presented in Cabrera-Arteaga et al. "CROW: Code Randomization of WebAssembly" *at proceedings of NDSS, Measurements, Attacks, and Defenses for the Web (MADWeb) 2021* `https://doi.org/10.14722/madweb.2021.23004`.
>
> CROW source code is available at `https://github.com/ASSERT-KTH/slumps`

3.2 MEWE: Multi-variant Execution for WebAssembly

This section describes MEWE [**?**]. MEWE synthesizes diversified function variants by using CROW. It then provides execution-path randomization in a Multivariant Execution (MVE) [**?**]. MEWE generates application-level multivariant binaries without changing the operating system or Wasm runtime. It creates an MVE by intermixing functions for which CROW generates variants, as illustrated by the green square in Figure 3.1. MEWE inlines function variants when appropriate, resulting in call stack diversification at runtime.

As illustrated in Figure 3.3, MEWE takes the LLVM IR variants generated by CROW's diversifier. It then merges LLVM IR variants into a Wasm multivariant. In the figure, we highlight the two components of MEWE, *Multivariant Generation* and the *Mixer*. In the *Multivariant Generation* process, MEWE gathers the LLVM IR variants created by CROW. The Mixer component, on the other hand, links the multivariant binary and creates a new entrypoint for the binary called *entrypoint tampering*. The tampering is needed in case the output of CROW are variants of the original entrypoint, e.g. the *main* function. Concretely, it wraps the dispatcher for the entrypoint variants as a new function for the final Wasm binary and is declared as the application entrypoint. The random generator is needed to perform the execution-path randomization. For the random generator, we rely on WASI's specification [**?**] for the random behavior of the dispatchers. However, its exact implementation is dependent on the platform on which the binary is deployed. Finally, using the same custom Wasm LLVM backend as CROW, we generate a standalone multivariant Wasm binary. Once generated, the multivariant Wasm binary can be deployed to any Wasm engine.

3.2.1 Multivariant generation

The key component of MEWE consists of combining the variants into a single binary. The core idea is to introduce one dispatcher function per original function with variants. A dispatcher function is a synthetic function in charge of choosing a variant at random when the original function is called. With the introduction of the dispatcher function, MEWE turns the original call graph into a multivariant call graph, defined as follows.

In Figure 3.4, we show the original static call graph for an original program (top of the figure), as well as the multivariant call graph generated with MEWE (bottom of the figure). The gray nodes represent function variants, the green nodes function dispatchers, and the yellow nodes are the original functions. The directed edges represent the possible calls. The original program includes three functions. MEWE generates 43 variants for the first function, none for the second, and three for the third. MEWE introduces two dispatcher nodes for the first and third functions. Each dispatcher is connected to the corresponding function variants to invoke one variant randomly at runtime.
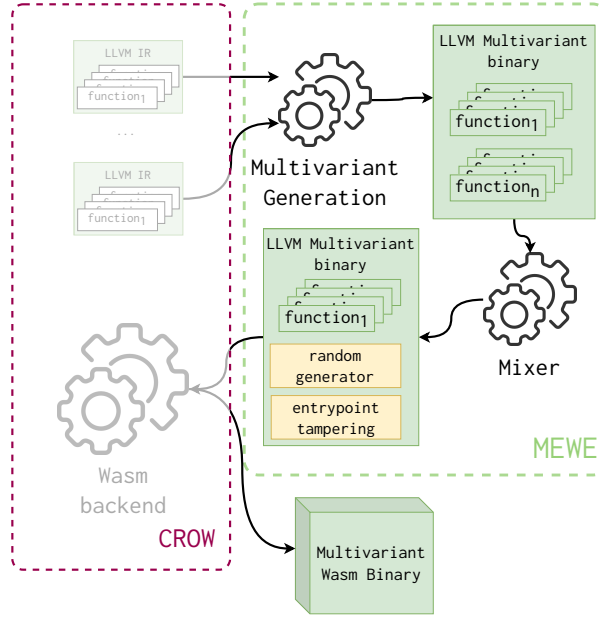
Figure 3.3: *Overview of MEWE workflow. It takes as input an LLVM binary. It first generates a set of functionally equivalent variants for each function in the binary using CROW. Then, MEWE generates an LLVM multivariant binary composed of all the function variants. Finally, the Mixer includes the behavior in charge of selecting a variant when a function is invoked. Finally, the MEWE mixer composes the LLVM multivariant binary with a random number generation library and tampers the original application entrypoint. The final process produces a Wasm multivariant binary ready to be deployed. Figure partially taken from [?].*

```
2   ; Multivariant foo wrapping ;
3   define internal i32 @foo(i32 %0) {
4       entry:
5           ; It first calls the dispatcher to discriminate between the created
                variants ;
6           %1 = call i32 @discriminate(i32 3)
7           switch i32 %1, label %end [
8             i32 0, label %case_43_
9             i32 1, label %case_44_
10          ]
11      ;One case for each generated variant of foo ;
12      case_43_:
13        %2 = call i32 @foo_43_(%0)
14        ret i32 %2
15      case_44_:
16        ; MEWE can inline the body of the a function variant ;
17        %3 = <body of foo_44_ inlined>
18        ret i32 %3
19      end:
20        ; The original is also included ;
21        %4 = call i32 @foo_original(%0)
22        ret i32 %4
23  }
```

Listing 3.7: *Dispatcher function embedded in the multivariant binary of the*
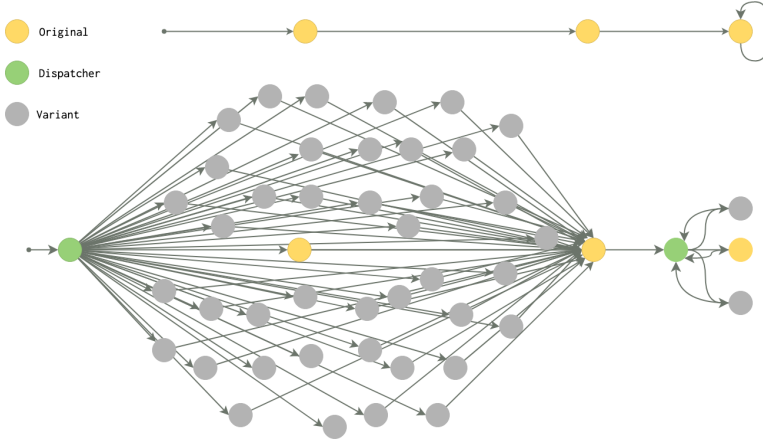
Figure 3.4: *Example of two static call graphs. At the top, is the original call graph, and at the bottom, is the multivariant call graph, which includes nodes that represent function variants (in gray), dispatchers (in green), and original functions (in yellow). Figure taken from [**?**].*

TODO Recheck these works on the decision of using switch cases to double check.

In Listing 3.7, we demonstrate how MEWE constructs the function dispatcher, corresponding to the rightmost green node in Figure 3.4, which handles three created variants including the original. The dispatcher function retains the same signature as the original function. Initially, the dispatcher invokes a random number generator, the output of which is used to select a specific function variant for execution (as seen on line 6 in Listing 3.7). To enhance security, we employ a switch-case structure within the dispatcher, mitigating vulnerabilities associated with speculative execution-based attacks [**?**] (refer to lines 12 to 19 in Listing 3.7). This approach also eliminates the need for multiple function definitions with identical signatures, thereby reducing the potential attack surface in cases where the function signature itself is vulnerable [**?**]. Additionally, MEWE can inline function variants directly into the dispatcher, obviating the need for redundant definitions (as illustrated on line 16 in Listing 3.7). Remarkably, we prioritize security over performance, i.e., while using indirect calls in place of a switch-case could offer constant-time performance benefits, we implement switch-case structures.

In Listing 3.7, we illustrate the LLVM construction for the function dispatcher corresponding to the right most green node of Figure 3.4. Notice that, the dispatcher function is constructed using the same signature as the original function. It first calls the random generator, which returns a value used to invoke a specific function variant (see line 6 in Listing 3.7). We utilize a switch-case structure in the dispatchers to prevent indirect calls, which are vulnerable to

speculative execution-based attacks [**?**] (see lines 12 to 19 in Listing 3.7), i.e., the choice of a switch-case also avoids having multiple function definitions with the same signature, which could increase the attack surface in case the function signature is vulnerable [**?**]. In addition, MEWE can inline function variants inside the dispatcher instead of defining them again (see line 16 in Listing 3.7). Remarkably, we trade security over performance since dispatcher functions that perform indirect calls, instead of a switch-case, could improve the performance of the dispatchers as indirect calls have constant time.

Contribution paper and artifact

MEWE provides dynamic execution path randomization by packaging variants generated out of CROW.
MEWE is fully presented in Cabrera-Arteaga et al. "Multi-Variant Execution at the Edge" *Proceedings of ACM, Moving Target Defense* `https://dl.acm.org/doi/abs/10.1145/3560828.3564007`

MEWE is also available as an open-source tool at `https://github.com/ASSERT-KTH/MEWE`

3.3 WASM-MUTATE: Fast and Effective Binary for WebAssembly

In this section, we introduce our third technical contribution, WASM-MUTATE [**?**], a tool that generates thousands of functionally equivalent variants out of a WebAssembly binary input. Leveraging rewriting rules and e-graphs [**?**] for software diversification, WASM-MUTATE synthesizes program variants by transforming parts of the original binary. In Figure 3.1, we highlight WASM-MUTATE as the blue squared tooling.

Figure 3.5 illustrates the workflow of WASM-MUTATE, which initiates with a WebAssembly binary as its input. The first step involves parsing this binary to create suitable abstractions, e.g. an intermediate representation. Subsequently, WASM-MUTATE utilizes predefined rewriting rules to construct an e-graph for the initial program, encapsulating all potential equivalent codes derived from the rewriting rules. The assurance of functional equivalence is rooted in the inherent properties of the individual rewrite rules employed. Then, pieces of the original program are randomly substituted by the result of random e-graph traversals, resulting in a variant that maintains functional equivalence to the original binary. WASM-MUTATE applies one transformation at a time. The output of one applied transformation can be chained again as an input WebAssembly binary, enabling the generation of many variants.
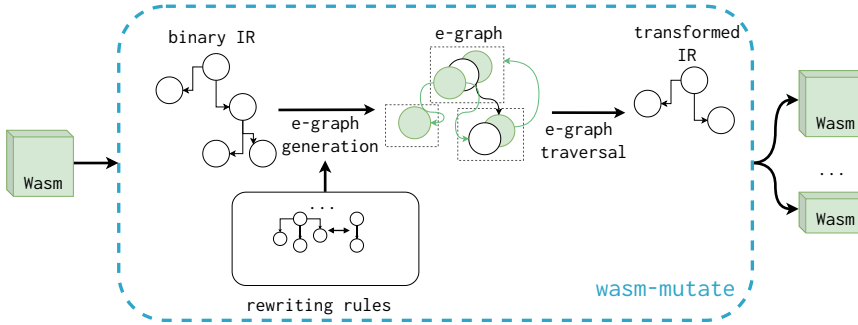
Figure 3.5: *WASM-MUTATE high-level architecture. It generates functionally equivalent variants from a given WebAssembly binary input. Its central approach involves synthesizing these variants by substituting parts of the original binary using rewriting rules, boosted by diversification space traversals using e-graphs.*

3.3.1 WebAssembly Rewriting Rules

WASM-MUTATE contains a comprehensive set of 135 rewriting rules. In this context, a rewriting rule is a tuple (`LHS, RHS, Cond`) where `LHS` specifies the segment of binary targeted for replacement, `RHS` describes its functionally equivalent substitute, and `Cond` outlines the conditions that must be met for the replacement to take place, e.g. enhancing type constraints. WASM-MUTATE groups these rewriting rules into meta-rules depending on their target inside a Wasm binary, ranging from high-level changes affecting binary section structure to low-level modifications within the code section. This section focuses on the biggest meta-rule implemented in WASM-MUTATE, the `Peephole` meta-rule [2].

Rewriting rules inside the *Peephole* meta-rule, operate over the data flow graph of instructions within a function body, representing the lowest level of rewriting. In WASM-MUTATE, we have implemented 125 rewriting rules specifically for this category, each one avoiding targeting instructions that might induce undefined behavior, e.g., function calls.

Moreover, we augment the internal representation of a Wasm program to bolster WASM-MUTATE's transformation capabilities through the `Peephole` meta-rule. Concretely, we augment the parsing stage in WASM-MUTATE by including custom operator instructions. These custom operator instructions are designed to use well-established code diversification techniques through rewriting rules. In practice, custom operators are only part of the rewriting rules of WASM-MUTATE. This means that, when parsing Wasm to the intermediate representation no custom operator is generated. When converting back to the WebAssembly binary format from the intermediate representation, custom instructions are meticulously handled to retain the original functionality of the

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[2]For an in-depth explanation of the remaining meta-rules, refer to [**?**].

WebAssembly program. Remarkably, custom operators highlight the versatility of WASM-MUTATE as a general-purpose binary rewriting engine.

In the example below, we illustrate a rewriting rule of the `Peephole` meta-rule that leverages a custom operator to insert `nop` instructions into any WebAssembly program place, a well-known low-level diversification strategy [**?**], while using the `container` custom operator. When generating the Wasm variant, the `container` custom operator is removed while its operands are encoded back to Wasm in their corresponding opcodes.

```
LHS x
```

```
RHS (container (x nop))
```

3.3.2 E-Graphs traversals

We developed WASM-MUTATE leveraging e-graphs, a specific graph data structure for representing and applying rewriting rules [**?**]. In the context of WASM-MUTATE, a primer e-graph is constructed from the input WebAssembly program. This initial e-graph is subsequently augmented with e-nodes and e-classes derived from each one of the rewriting rules (we detail the e-graph construction process in Section 3 of [**?**]).

Willsey et al. highlight the potential for high flexibility in extracting code fragments from e-graphs, a process that can be recursively orchestrated through a cost function applied to e-nodes and their respective operands. This methodology ensures the functional equivalence of the derived code [**?**]. For instance, e-graphs solve the problem of providing the best code out of several optimization rules [**?**]. To extract the "optimal" code from an e-graph, one might commence the extraction at a specific e-node, subsequently selecting the AST with the minimal size from the available options within the corresponding e-class's operands. In omitting the cost function from the extraction strategy leads us to a significant property: *any path navigated through the e-graph yields a functionally equivalent code variant.*

We exploit such property to fastly generate diverse WebAssembly variants. We propose and implement an algorithm that facilitates the random traversal of an e-graph to yield functionally equivalent program variants, as detailed in Algorithm 1. This algorithm operates by taking an e-graph, an e-class node (starting with the root's e-class), and a parameter specifying the maximum extraction depth of the expression, to prevent infinite recursion. Within the algorithm, a random e-node is chosen from the e-class (as seen in lines 5 and 6), setting the stage for a recursive continuation with the offspring of the selected e-node (refer to line 8). Once the depth parameter reaches zero, the algorithm extracts the most concise expression available within the current e-class (line

3). Following this, the subexpressions are built (line 10) for each child node, culminating in the return of the complete expression (line 11).

Algorithm 1 e-graph traversal algorithm taken from [**?**].

1: **procedure** TRAVERSE($egraph$, $eclass$, $depth$)
2:     **if** depth $= 0$ **then**
3:         **return smallest__tree__from**(egraph, eclass)
4:     **else**
5:         $nodes \leftarrow egraph[eclass]$
6:         $node \leftarrow random\_choice(nodes)$
7:         $expr \leftarrow (node, operands = [])$
8:         **for each** $child \in node.children$ **do**
9:             $subexpr \leftarrow$ **TRAVERSE**($egraph$, $child$, $depth - 1$)
10:             $expr.operands \leftarrow expr.operands \cup \{subexpr\}$
11:         **return** $expr$

3.3.3 WASM-MUTATE instantiation

Let us illustrate how WASM-MUTATE generates variant programs by using the before enunciated algorithm. Here, we use Algorithm 1 with a maximum depth of 1. In Listing 3.8 a hypothetical original Wasm binary is illustrated. In this context, a potential user has set two pivotal rewriting rules: `(x, container (x nop),)` and `(x, x i32.add 0, x instanceof i32)`. The former rule, which has been previously discussed in Subsection 3.3.1, grants the ability to append a `nop` instruction to any subexpression. Conversely, the latter rule adds zero to any numeric value .
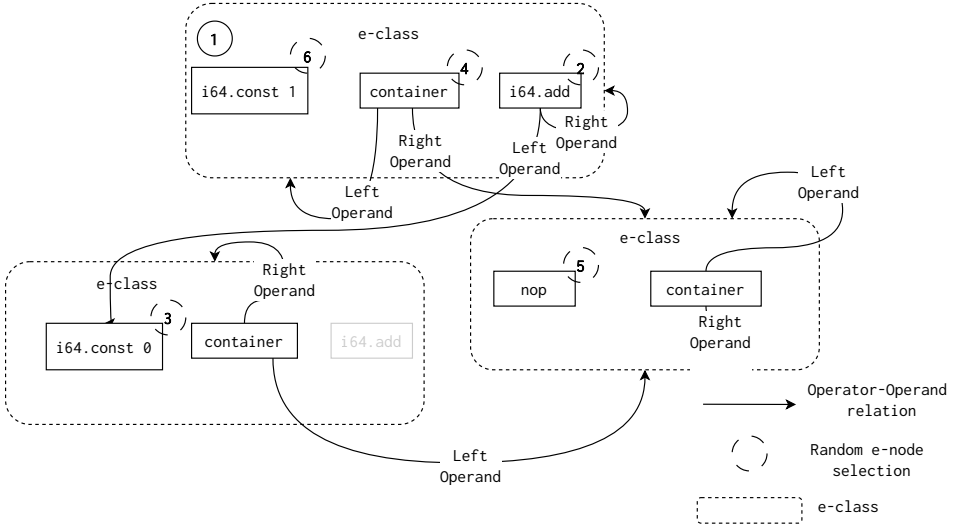
Figure 3.6: *e-graph built for rewriting the first instruction of Listing 3.8.*

```
(module
    (type (;0;) (func (param i32 f32) (result i64)))
    (func (;0;) (type 0) (param i32 f32) (result i64)
        i64.const 1)
)
```

Listing 3.8: *Wasm function.*

```
(module
    (type (;0;) (func (param i32 f32) (result i64)))
    (func (;0;) (type 0) (param i32 f32) (result i64)
        (i64.add (
            i64.const 0
            i64.const 1
            nop
        ))
    )
```

Listing 3.9: *Random peephole mutation using egraph traversal for Listing 3.8 over e-graph Figure 3.6. The textual format is folded for better understanding.*

Leveraging the code presented in Listing 3.8 alongside the defined rewriting rules, we build the e-graph, simplified in Figure 3.6. In the figure, we highlight various stages of Algorithm 1 in the context of the scenario previously described. The algorithm initiates at the e-class with the instruction `i64.const 1`, as seen in Listing 3.8. At ②, it randomly selects an equivalent node within the e-class, in this instance taking the `i64.add` node, resulting: `expr`

= `i64.add l r`. As the traversal advances, it follows on the left operand of the
previously chosen node, settling on the `i64.const 0` node within the same e-
class ③. Then, the right operand of the `i64.add` node is choosen, selecting the
`container` ④ operator yielding: `expr = i64.or (i64.const 0 container (`
`r nop ))`. The algorithm chooses the right operand of the `container` ⑤, which
correlates to the initial instruction e-node highlighted in ⑥, culminating in
the final expression: `expr = i64.or (i64.const 0 container( i64.const 1`
`nop)) i64.const 1`. As we proceed to the encoding phases, the `container`
operator is ignored as a real Wasm instruction, finally resulting in the program
in Listing 3.9.

Notice that, within the e-graph showcased in Figure 3.6, the container node
maintains equivalence across all e-classes. Consequently, increasing the depth
parameter in Algorithm 1 would potentially escalate the number of viable variants
infinitely.

Contribution paper and artifact

WASM-MUTATE leverages random traversals over e-graphs to provide a
binary-based solution for WebAssembly diversification.
WASM-MUTATE is fully presented in Cabrera-Arteaga et al. "WASM-
MUTATE: Fast and Effective Binary Diversification for WebAssembly"
`https://arxiv.org/pdf/2309.07638.pdf`.

WASM-MUTATE is available at `https://github.com/bytecodeallia`
`nce/wasm-tools/tree/main/crates/wasm-mutate` as a contribution to
the bytecodealliance organization [a].

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[a] `https://bytecodealliance.org/`

3.4 Comparing CROW, MEWE, and WASM-MUTATE

In this section, we compare CROW, MEWE, and WASM-MUTATE, highlighting
their key differences. These distinctions are summarized in Table 3.1. The table
is organized into columns that represent attributes of each tool: the tool's name,
input format, core diversification strategy, number of variants generated within
an hour, targeted sections of the WebAssembly binary for diversification, strength
of the generated variants, and the security applications of these variants. Each
row in the table corresponds to a specific tool. Notice that, the data and insights
presented in the table are sourced from the respective papers of each tool and,
from the previous discussion in this chapter.

Tool	Input	Core	Variants in 1h	Target	Variants Strength	Security applications
CROW	Source code or LLVM Ir	Enumerative synth.	> 1k	Code section	**96%**	Static analysis and side-channel attacks.
MEWE	Source code or LL VM Ir	CROW, Execution path randomization	> 1k	Code and Function sections	**96%**	Static and dynamic analysis, web timing-based attacks.
WASM-MUTATE	rewriting rules, **Wasm bin.**	e-graph random traversals	**> 10k**	**Any Wasm part**	76%	Signature-based identification, static analysis, compiler fingerprinting and timing side-channel attacks.

Table 3.1: *Comparing CROW, MEWE and WASM-MUTATE. The table columns are: the tool's name, input format, core diversification strategy, number of variants generated within an hour, targeted sections of the WebAssembly binary, strength of the generated variants, and the security applications of these variants. The* Variant strength *accounts for the capability of each tool on generating variants that are preserved after the JIT compilation of V8 and wasmtime in average. Our three technical contributions are complementary tools that can be combined.*

CROW is a compiler-based strategy, needing access to the source code or its LLVM IR representation to work. Its core is an enumerative synthesis implementation with functionallity verification using SMT solvers, ensuring the functional equivalence of the generated variants. In addition, MEWE extends the capabilities of CROW, utilizing the same underlying technology to create program variants. It goes a step further by packaging the LLVM IR variants into a Wasm multivariant, providing MVE through execution path randomization. Both CROW and MEWE are fully automated, requiring no user intervention besides the input source code. WASM-MUTATE, on the other hand, is a semi-automated, binary-based tool. It needs a set of rewriting rules and the Wasm binary as inputs to generate program variants, centralizing its core around random e-graph traversals. Remarkably, WASM-MUTATE removes the need for compiler adjustments, offering compatibility with any existing WebAssembly binary.

We have observed several interesting phenomena when aggregating the empirical data presented in the corresponding papers of CROW, MEWE and WASM-MUTATE [**?** **?** **?**]. This can be appreciated in the fourth, fifth and sixth columns of Table 3.1. We have observed that WASM-MUTATE generates more unique variants in one hour than CROW and MEWE in at least one order of magnitude. This is mainly because WASM-MUTATE can generate variants in any part of the Wasm binary, while CROW and MEWE are limited to the code and function sections. In addition, CROW and MEWE generation capabilities are limited by the *overlapping* phenomenon discussed in Subsection 3.1.3. On the other hand, CROW and MEWE, by using enumerative synthesis, can exceed handcrafted optimizations [**?**], ensuring that the generated variants are preserved. In other words, the transformations generated out of CROW and MEWE are virtually irreversible by JIT compilers, such as V8 and wasmtime. This phenomenon is highlighted in the *Variants strength* column of Table 3.1, where we show that CROW and MEWE generate variants with 96% of preservation against 75% of WASM-MUTATE.

Takeaway

Our three technical contributions serve as complementary tools that can be combined. For instance, when the source code for a WebAssembly binary is either non-existent or inaccessible, WASM-MUTATE offers a viable solution for generating code variants. On the other hand, CROW and MEWE excel in scenarios where high preservation is crucial. Furthermore, WASM-MUTATE can benefit from the enumerative synthesis techniques employed by CROW and MEWE. Specifically, WASM-MUTATE could incorporate the transformations generated by these tools as rewriting rules.

3.4.1 Security applications

The last column of Table 3.1 highlights the security applications of the variants generated by our three technical contributions. The first direct consequence of changing the structure of Wasm binaries from variant to variant is that signature-based identification is mitigated, i.e. static analysis is hardened. Moreover, our tools generate many different and highly preserved code variants. This means that these variants, each with unique WebAssembly codes, maintain their distinctiveness even after JIT compilers translate them into machine codes (see Subsection 2.1.5). The preservation feature significantly reduces the impact of side-channel attacks that exploit specific machine code instructions, e.g., port contention [**?**].

Altering the layout of a WebAssembly program inherently influences its managed memory during runtime, a component not overseen by the WebAssembly program itself (see Definition 1). This pehomenon is especially important for CROW and MEWE, given that they do not directly address the WebAssembly memory model. Significantly, CROW and MEWE considerably alter the managed memory by modifying the layout of the WebAssembly program. For example, the *constant inferring* transformations significantly alter the layout of program variants, affecting unmanaged memory elements such as the returning address of a function. Furthermore, WASM-MUTATE not only affects managed memory through changes in the WebAssembly program layout. It also adds rewriting rules to transform unmanaged memory instructions. Memory alterations, either to the unmanaged or managed memories, have substantial security implications, by eliminating potential jump points that facilitate malicious activities within the binary [**?**].

Besides, our technical contributions enhance security against timing-based attacks by creating variants that exhibit a wide range of execution times. This strategy is especially prominent in MEWE's approach, which develops multivariants functioning on randomizing execution paths, thereby thwarting attempts at timing-based inference attacks [**?**]. Adding another layer benefit, the integration of diverse variants into multivariants can potentially disrupt dynamic analysis tools such as symbolic executors [**?**]. Concretely, different control flows through a random discriminator, exponentially increase the number of possible execution paths, making multivariant binaries virtually unexplorable.

Takeaway

CROW, MEWE and WASM-MUTATE generate WebAssembly variants that can be used to enhance security. Overall, they generate variants that are suitable for hardening static and dynamic analysis, side-channel attacks, to thwart signature-based identification and compiler fingerprinting.

3.5   Conclusions

In this chapter, we discuss the technical specifics underlying our primary technical contributions. We elucidate the mechanisms through which CROW generates program variants. Subsequently, we discuss MEWE, offering a detailed examination of its role in forging MVE for WebAssembly. We also explore the details of WASM-MUTATE, highlighting its pioneering utilization of an e-graph traversal algorithm to spawn Wasm program variants. Remarkably, we undertake a comparative analysis of the three tools, highlighting their respective benefits and limitations, alongside the potential security applications of the generated Wasm variants.

In Chapter 4, we present two use cases that support the exploitation of these tools. Chapter 4 serves to bridge theory with practice, showcasing the tangible impacts and benefits realized through the deployment of CROW, MEWE, and WASM-MUTATE.

4

EXPLOITING SOFTWARE DIVERSIFICATION FOR WEBASSEMBLY

In this chapter ...

4.1 Offensive Diversification: Malware evasion

Discussion In this section we mention some challenges we face during the writing of this work. We enumerate them in order to enforce the debase and the discussion on the topic.

Oracle classification moves in time: One could expect that the more detectors a binary has, the more iterations are needed to evade them. However, we have observed that this is not the case for some binaries. The main reason is that the final labelling of binaries for VirusTotal vendors is not immediate [**?**]. For example, a VirusTotal vendor could label a binary as benign and change it later to malign after several weeks in a conservative way of acting. This phenomenon creates a time window in which slightly changed binaries (fewer iterations in our case) could evade the detection of numerous vendors.

Lack of bigger picture: A WebAssembly cryptomalware can only exist with its JavaScript complement. For example, a browser cryptonalware needs to send the calculated hashes to a cryptocurrency service. This network communication is outside the WebAssembly accesses and needs to be delegated to a JavaScript code. Besides, other functionalities can be intermixing between JavaScript and WebAssembly and in some cases be completely in one side or the other [**?**]. This intermixing between JavaScript and WebAssembly could provide statically different WebAssembly. We have observed that, the imports and the memory data of the WebAssembly binaries have a high variability in our original dataset.

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The imported functions from JavaScript change from binary to binary. Their data segments can also differ in content and length. To completely analyze these cases, the whole JavaScript-WebAssembly program is needed, something only provided in 9/33 cases of our dataset.

More narrowed fitness function: We use a simple fitness function, but the MCMC evasion algorithm could have a fitness function as general as wanted. In our case, we do not use binary metadata, instead we focus on the result from the malware oracle, given that the main goal is to evade this oracle.

Mitigation: **TODO** TBD, data augmentation, better resilience evaluation ?

Another interesting thing would be to see if there is difference in the detectors. If some detectors are fooled by some transformations or are more robust, etc.

TODO Motivate the use case with the following sota

Binary rewriting tools and obfuscators The landscape for tools that can modify, obfuscate, or enhance WebAssembly binaries for various has increased. For instance, BREWasm[**?**] provides a comprehensive static binary rewriting framework specifically designed for WebAssembly. Wobfuscator[**?**] takes a different approach, serving as an opportunistic obfuscator for Wasm-JS browser applications. Madvex[**?**] focuses on modifying WebAssembly binaries to evade malware detection, with its approach being limited to alterations in the code section of a WebAssembly binary. Additionally, WASMixer[**?**] obfuscates WebAssembly binaries, by including memory access encryption, control flow flattening, and the insertion of opaque predicates.

TODO The malware evasion paper

4.1.1 Threat model and objective

Test and evade the resilience of WebAssembly malware detectors mentioned in Subsection 2.1.5.

4.1.2 Approach

TODO We use wasm-mutate   **TODO** How do we use it?   **TODO** Controlled and uncontrolled diversification.
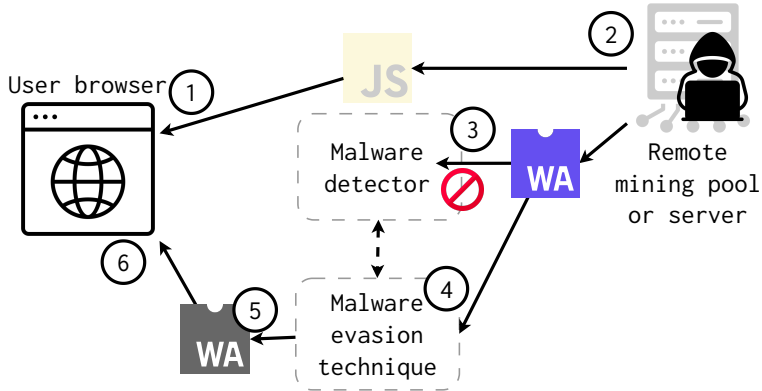
Figure 4.1: *Taken from [?]*

4.1.3 Results

> **Contribution paper**
>
> The case discussed in this section is fully detailed in Cabrera-Arteaga et al. "WebAssembly Diversification for Malware Evasion" *at Computers & Security, 2023* `https://www.sciencedirect.com/science/article/pii/ S0167404823002067`.

4.2 Defensive Diversification: Speculative Side-channel protection

TODO Go around the last paper

4.2.1 Threat model

- Spectre timing cache attacks.
    - Rockiki paper on portable side channel in browsers.

4.2.2 Approach

- Use of wasm-mutate

4.2.3 Results

- Diminshing of BER

> **Contribution paper**
>
> The case discussed in this section is fully detailed in Cabrera-Arteaga
> et al. "WASM-MUTATE: Fast and Effective Binary Diversification for
> WebAssembly" *Under review* `https://arxiv.org/pdf/2309.07638.pdf`.

TODO TBD discuss deoptimization

4.2.4 Partial input/output validation

When WASM-MUTATE generates a variant, it can be executed to check the
input/output equivalence. If the variant has a _start function, both binaries, the
original and the variant can be initialized. If the state of the memory, the globals
and the stack is the same after executing the _start function, they are partially
equivalent.

The _start function is easier to execute given its signature. It does not receive
parameters. Therefore, it can be executed directly. Yet, since a WebAssembly
program might contain more than one function that could be indistinctly called
with and arbitrary number of parameters, we are not able to validate the whole
program. Thus, we call the checking of the initialization of a Wasm variant, a
partial validation.

4.2.5 Some other works to be cited along with the paper. Mostly in the Intro

Spectre and side-channel defenses

- paper 2021: Read this, since it is super related, `https://www.isecure-jo`
`urnal.com/article_136367_a3948a522c7c59c65b65fa87571fde7b.pdf` [**?**]

- A dataset of Wasm programs: [**?**]

- Papers 2020

- Papers 2019 - [**?**]

Selwasm: A code protection mechanism for webassembly

Babble

- https://arxiv.org/pdf/2212.04596.pdf

Principled Composition of Function Variants for Dynamic Software Diversity
and Program Protection

- https://dl.acm.org/doi/10.1145/3551349.3559553

How Far We've Come – A Characterization Study of Standalone WebAssembly
Runtimes

- https://ieeexplore.ieee.org/document/9975423
Code obfuscation against symbolic execution attacks
Code artificiality: A metric for the code stealth based on an n-gram model
Semantics-aware obfuscation scheme prediction for binary
Wobfuscator: Obfuscating javascript malware via opportunistic translation to webassembly
Synthesizing Instruction Selection Rewrite Rules from RTL using SMT "We also synthesize integer rewrite rules from WebAssembly to RISC-V "
Wafl: Binary-only webassembly fuzzing with fast snapshots

4.3 Conclusions

5

CONCLUSIONS AND FUTURE WORK

5.1 Summary of technical contributions

5.2 Summary of empirical findings

5.3 Future Work

Moreover, the WebAssembly ecosystem is still in its infancy compared to more mature programming environments. A 2021 study by Hilbig et al. found only 8,000 unique WebAssembly binaries globally[**?**], a fraction of the 1.5 million and 1.7 million packages available in npm and PyPI, respectively. This limited dataset poses challenges for machine learning-based analysis tools, which require extensive data for effective training. The scarcity of WebAssembly programs also exacerbates the problem of software monoculture, increasing the risk of compromised WebAssembly programs being consumed[**?**]. This dissertation aims to mitigate these issues by introducing a comprehensive suite of tools designed to enhance WebAssembly security through Software Diversification and to improve testing rigor within the ecosystem.

Program Normalization WASM-MUTATE was previously employed successfully for the evasion of malware detection, as outlined in [**?**]. The proposed mitigation in the prior study involved code normalization as a means of reducing the spectrum of malware variants. Our current work provides insights into the potential effectiveness of this approach. Specifically, a practically costless process of pre-compiling Wasm binaries could be employed as a preparatory measure for malware classifiers. In other words, a Wasm binary can first be compiled with wasmtime, effectively eliminating approx. 25% of malware variants according to our preservation statistics for wasmtime. This approach could substantially enhance the efficiency and precision of malware detection systems.

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Part II

Included papers

SUPEROPTIMIZATION OF WEBASSEMBLY BYTECODE

Javier Cabrera-Arteaga, Shrinish Donde, Jian Gu, Orestis Floros, Lucas Satabin, Benoit Baudry, Martin Monperrus
Conference Companion of the 4th International Conference on Art, Science, and Engineering of Programming (Programming 2021), MoreVMs

CROW: CODE DIVERSIFICATION FOR WEBASSEMBLY

Javier Cabrera-Arteaga, Orestis Floros, Oscar Vera-Pérez, Benoit Baudry, Martin Monperrus
Network and Distributed System Security Symposium (NDSS 2021), MADWeb

MULTI-VARIANT EXECUTION AT THE EDGE

Javier Cabrera-Arteaga, Pierre Laperdrix, Martin Monperrus, Benoit Baudry
Conference on Computer and Communications Security (CCS 2022), Moving Target Defense (MTD)

WEBASSEMBLY DIVERSIFICATION FOR MALWARE EVASION

Javier Cabrera-Arteaga, Tim Toady, Martin Monperrus, Benoit Baudry

WASM-MUTATE: FAST AND EFFECTIVE BINARY DIVERSIFICATION FOR WEBASSEMBLY

Javier Cabrera-Arteaga, Nick Fitzgerald, Martin Monperrus, Benoit Baudry
Under revision

SCALABLE COMPARISON OF JAVASCRIPT V8 BYTECODE TRACES

Javier Cabrera-Arteaga, Martin Monperrus, Benoit Baudry
11th ACM SIGPLAN International Workshop on Virtual Machines and Intermediate Languages (SPLASH 2019)